GEOLOGICAL FEATURES AND RESURFACING HISTORY OF EUROPA.

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Introduction

Many different models have been proposed for the formation of Europa's primary surface features: ridges, bands, chaos and lenticulae. We briefly review the models, evaluating their strengths and weaknesses, and their implications for the thickness of Europa's ice shell. We discuss Europa's stratigraphy, and how the surface may have evolved through time.

Morphological features

Ridges: Double ridges are without doubt the most ubiquitous feature on Europa's surface. They are highly unusual in the solar system, and have only been identified on Triton to date [1]. The Europan ridges constitute an intricate mesh, they have formed throughout Europa's visible history and may still be forming today [e.g., 2]. Ridges appear to form a genetic sequence of different morphological types, ranging from simple troughs, through double ridges, then triple ridges, and finally any number of closely spaced ridges, termed "ridge complexes" [2, 3]. The dominant type by far is the double ridge, which has two crests of largely uniform width and height, separated by a V-shaped trough. Ridges range in size, from ~500 hundred m to ~2 km wide, up to ~200 m high, and up to several thousand km in length, meaning that some are hemispherical in scale. Cycloidal ridges appear to form on relatively rapid timescales resulting from Europa's diurnal cycle [4], but the details of how the majority of Europa's ridges are created are still open to debate.

Several models have been proposed for the formation of the ridges, each of which has its strengths and weaknesses. These include: (1) *Tidal squeezing*, in which fractures penetrate through an ice shell, and open and close as a result of diurnal stresses [5]. The amount of opening and closing is small – about 1 m – and each cycle allows water and icy slush to be pumped toward the surface, forming the characteristic ridge crests and central trough. This process is similar to that which forms terrestrial pressure ridges in lead ice, and the morphology is remarkable similar. (2) *Compression*, in which ridges are proposed to have a compressional origin [6]. This model could help account for the mystery of Europa's surface, which has abundant evidence of extension, but little identified compression. While falling out of favor for a few years, this model has recently been revived by [7]. (3) *Linear volcanism*, in which ridges are proposed to be the result of gas-driven fissure eruptions, resulting in ridge crests comprised of cryoclastic debris [8]. Volatiles SO_2 and CO_2 could drive the eruptions. (4) *Linear diapirism*, a model in which ridges are proposed as the surface expression of linear warm ice diapirs, which rise to the surface, causing cracking and uplift of the surrounding terrain, forming ridge flanks [9]. (5) *Dike intrusion*, in which ridges form by intrusion of melt into vertical cracks, resulting in plastic deformation to form ridge morphology [10]. (6) *Shear heating*, in which heating along cracks from diurnal strike-slip motion causes upwelling of warm ice to form ridges, with possible associated partial melting [11]. To date, none of these models can describe all the features characteristic of ridges, such as uniformity in space and time, forks, and sharp turns.

Bands: Bands are features up to tens of km wide and hundreds of km long, which apparently brighten with age. They have formed through complete separation of the preexisting surface, by extension, shear and/or compression [12, 13]. Two primary models have been proposed for the formation of bands. The first suggests that they are a continuation of the tidal-squeezing ridge forming process [5], and that they result from continuous ratcheting apart of a crack due to diurnal stresses and the possible influence of secular variations [14]. The rising water is proposed to freeze, preventing the crack from closing, and is then pulled further apart during the next tidal cycle, adding more frozen material and widening the band. This model implies that Europa's ice shell is relatively thin. The second model proposes that bands have an origin similar to that of mid-ocean ridges [15], and that they form from solid-state material, possibly ductile warm ice [16]. As with the previous model, new material is added along the band's central axis, but it is solid state, and the resulting band morphology may depend on the rate of band opening. This model does not require a thin shell.

Lenticulae: Lenticulae are the many subcircular areas of disrupted terrain present across Europa's surface. They range in size but are generally agreed to cluster around ~10 km in diameter [e.g., 2, 17]. Lenticulae can be either pits, domes, low albedo plains areas, or some combination of these. Many of them (known as microchaos) have interiors which are broken into small plates of preexisting surface material in a lower albedo matrix [2]. Two primary models have been proposed for their origin. The first, based on their apparently uniform size distribution, suggests that they are the result of diapirism [18, 19], possibly due to thickening of the ice shell to a point at which convection can be initiated. The second, based on the resemblence of plates within the lenticulae to terrestrial icebergs, suggests that they result from melting of the surface by liquid water [20, 21] requiring a much thinner shell. Lenticulae may be related to the formation of chaos.

Chaos: Chaos regions are much larger than lenticulae, but are also areas of Europa's surface that appear to have been significantly disrupted by some endogenic (cryo)magmatic process. Although there are morphological variations, chaos terrain is comprised of polygonal plates of preexisting surface material, in a dark, finer grained hummocky matrix [2]. In at least one area, there is evidence that the plates have shifted from their original position [22], and chaos may stand either higher or lower than its surroundings [2, 23]. As with the lenticulae, the two models proposed for chaos formation are that they formed from regions of liquid water melt-through [20, 21], or from single or merged diapirs of warm ice [18]. Each model has significant implications for the thickness of the shell.

Resurfacing history

Image coverage and resolution from the Galileo spacecraft has been sufficient to allow several local and regional areas on Europa to be mapped, and a stratigraphy to be derived [2, 24]. Recent pole-to-pole mapping [25] considerably extends earlier work over a much broader area of coverage, and confirms previous suggestions that there has been an apparent change in the style of resurfacing on Europa over time. The visible history of Europa only goes back as far as the "background ridged plains" which comprise most of Europa. This unit is so heavily tectonized that it is very hard to determine the existence of any preexisting features within it; Europa has either been completely resurfaced prior to background plains formation, or features that existed prior to its formation are so completely tectonized as to be unrecognizable. Either way, the average surface age of Europa is estimated to be ~60 Ma [26].

Postdating the formation of the background plains, the next oldest group of features are the gray bands. Bands have a variety of orientations and commonly cross-cut each other, but none appear to have formed in Europa's recent history. Whether formed from liquid water or warm ice, they suggest a change in resurfacing style to magmatic processes. Chaos and lenticulae commonly postdate bands, although it is impossible to tell whether they themselves formed concurrently. Since chaos-related features are some of the youngest units in Europa's stratigraphic column, it is possible that they are still forming today. This inference has significant implications for Europa's astrobiological potential, since such features may be places where its ocean communicates with the surface. Double ridges and craters are found throughout Europa's visible surface history, although tectonic lineaments have been found to narrow over time, perhaps indicating a change in the thermal state of Europa's ice shell [25].

The change in the formation from bands (lateral tectonics with associated cryomagmatism) to chaos (vertical transport of cryomagmatic materials) has been suggested as evidence that Europa's shell may be undergoing progressive thickening with time, possibly as a result of the "freezing out" of an ocean [16, 24, 25, 27]. Such thickening may explain the change from the inferred earlier mobility of the ice shell, in which lithospheric separation, and hence band formation, was common, to a convective state in which lenticulae and chaos are the norm.

The apparent change in Europa's resurfacing style is not sufficient to place this transition into a longer-term context [25, 27]. Because Europa's surface is so young, on average, we cannot tell from currently available data whether the apparent thickening of the ice shell corresponds to the complete cessation of geological activity, whether both processes coexist in different regions, or whether there are cycles of alternating tectonic and cryovolcanic activity, on geological timescales.

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